NASA SP-354

DOT/NASA COMPARATIVE ASSESSMENT OF BRAYTON ENGINES FOR GUIDEWAY VEHICLES AND BUSSES

VOLUME I—SUMMARY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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VOLUME I—SUMMARY

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PREFACE

The Department of Transportation (DOT) requested that the NASA Office of Aeronautics and Space Technology (OAST) evaluate and assess the potential of several types of gas turbine engines and fuels for the on-board power and propulsion of a future heavy-duty ground transportation system. This study began in 1971 and was conducted by the Lewis Research Center of OAST with the support of the Marshall Space Flight Center of the Office of Manner Space Flight (OMSF) in the area of fuels. Study coordination and review were provided by an interagency steering committee with representatives of the Federal Rail Administration, the Urban Mass Transportation Administration, the Transportation System Center, the Office of the Secretary of Transportation, the NASA Office of Aeronautics and Space Technology, and the NASA Office of Manned Space Flight as members. It was recognized that many of these systems had been analyzed independently but that no comparison on a common and consistent basis had been made with other systems. The purpose of this study was threefold: (1) to provide a definition of the potential for turbine engines to minimize pollution, energy consumption, and noise, (2) to provide a useful means of comparison of the types of engine based on consistent assumptions and a common analytical approach, and (3) to provide a compendium of comparative performance data that would serve as the technical basis for future planning.

Over the past several years the public has become increasingly aware of the shortcomings of present transportation systems. This awareness is reflected in legislative activity aimed at reducing noxious emissions, improving the ambient air quality of our major metropolitan centers, and arresting any further degradation of the environment in general. To this time, the major focus of action has been on the contribution of the automobile (light-duty vehicles) and its internal combustion engine. These actions come at the same time as the rising concern for the dwindling supplies of domestic petroleum and the economic and political implications of increased imports.

The heavy-duty ground transportation systems of the nation are characterized by a greater inability to change than light-duty vehicles. The average vehicle life varies from 15 years for a city bus to over 25 years for a locomotive. This factor requires consideration of long-term trends, particularly with respect to fuel supplies and alternative means of transportation. DOT is pursuing a program of investigation and demonstration of a variety of new transport modes, such as high-speed rail, tracked air-cushion vehicles (TACV), magnetically levitated vehicles, intensive use of public transport, and personal rapid transit (PRT) systems. DOT has recognized that it is important to evaluate the most promising options and trade-offs for on-board power and propulsion generation and electrification. It is this awareness that has stimulated the investigation presented in this report.

The emphasis of the study was on establishing comparison trends rather than on absolute values and a definitive engine selection. The primary value of this study is intended to be usefulness of the results to provide a quantitative basis for future judgment.

Contributions to this study were made by numerous individuals at the Lewis Research Center and the Manned Space Flight Center. To facilitate compilation of this report, each participant prepared the section of the report that dealt with his areas. Volume II of this report is the result of the integration of these individual contributions. It contains all of the results dealing with the engine comparisons and includes a study of the use of methane and hydrogen as fuels for future transportation systems and of cryogenic tankage for these fuels.

Because of the bulk of material in volume II, the main points, that is, a summary of the analysis results and conclusions, are in part I. The background and reasons for comparing open, closed, and semiclosed Brayton engines for heavy-duty transportation are discussed in the INTRODUCTION to volume I.

The study was managed by L. I. Shure and D. R. Packe. The report authors and the sections to which they contributed are listed in alphabetical order as follows:

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J. L. Anderson	Appendix F
D. G. Beremand	Appendix D

R. K. Burns	Volume I, sections 1 to 3; volume II, sections 2 to 5, and appendixes B and I
D. A. Cantoni	Volume II, section 5 and appendix C
K. C. Civinskas	Volume II, section 5 and appendix C
L. J. Gilbert	Volume II, section 5 and appendix C
S. H. Gorland	Volume II, appendix E
D. C. Guentert	Volume I, sections 1 to 4
M. F. Heidmann	Volume II, appendix D
K. W. Hiller	Volume II, appendix C
K. S. Jefferies	Volume II, sections 4 and 5 and appendix B
R. E. Jones	Volume II, appendix D
P. T. Kerwin	Volume II, appendixes A and D
J. L. Klann	Volume II, sections 4 and 5 and appendix B
T. S. Mroz	Volume II, appendix D
A. J. Pavli	Volume II, appendix H
E. J. Petrik	Volume II, appendix C
L. I. Shure	Volume I, sections 1 to 3; and volume II, section 2
H. B. Tryon	Volume II, appendix H
J. M. Winter	Volume II, appendix H

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B. J. Herman	Volume II, appendix G
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A. J. Finzel	Volume II, appendix G

The individual sections were integrated into the final form by R. K. Burns, P. T. Kerwin, and Sol H. Gorland.

CONTENTS

INTRODUCTION

The Department of Transportation (DOT) requested the National Aeronautics and Space Administration to assess the potential of Brayton cycle engines for future heavy-duty ground transportation. Brayton cycle engines (gas turbines) are of interest because of their potentials for low weight, low emissions, and multifuel capability. The continuous combustion in gas-turbine engines increases the design options available for reducing undesirable exhaust emissions compared with presently used intermittent combustion engines. Continuous combustion also increases the variety of fuels that can be used. The lower engine weight per unit power of gas turbines compared with presently used diesel engines is important, not only for air-cushion vehicles but also for more conventional road-vehicles. At high speeds the wear on road beds increases significantly. To reduce this wear, lower axle loadings are necessary at higher speeds. This, together with the fact that power requirements increase rapidly with vehicle speed, results in the need for much lower weight per unit power than is currently available with diesel engines. Also, for the same vehicle weight a lower engine weight allows a higher payload fraction, or for the same payload and power a lower engine weight allows higher vehicle acceleration.

Open-cycle, unrecuperated gas turbines have been under consideration for heavy-duty vehicles for at least 20 years. Numerous gas-turbine-powered locomotives have been built and tested. These have depended heavily on existing aircraft gas turbines and on existing power transmission systems. One of the biggest problems encountered has been that fuel consumption was generally 25 to 50 percent higher than for diesel engines in the same power range. This is due mainly to the undesirable decrease in the efficiency of a simple open-cycle gas turbine as power level is reduced from full power. This characteristic is much improved if a recuperated cycle is used. And recuperated engines have seen substantial development but limited application at power levels applicable to buses, trucks, and automobiles.

Because of the concern about the efficiency of open-cycle engines at off-design power levels, a closed Brayton cycle might be considered. A commonly cited attribute of closed Brayton cycles is their ability to maintain high efficiency over a wide range of power level. Power level is changed by adjusting the system gas inventory and hence pressure level and mass flow rate, while holding the turbine-inlet temperature and turbomachinery rotational speed constant. In contrast, the power level of an open-cycle Brayton is generally reduced by reducing the turbine-inlet temperature and rotational speed, and thus thermodynamic efficiency.

Since the compressor-inlet pressure of a closed-cycle Brayton engine could be above atmospheric pressure, the size of the turbomachinery and recuperator could be smaller than those of an open-cycle engine. However, the closed-cycle engine requires additional heat exchangers for waste-heat rejection, for heat transfer between the combustion gas and the Brayton cycle gas, and for air preheat in the combustion loop. As a result, the closed-cycle engine, while having better efficiency at off-design power level, is expected to be larger than an open-cycle engine with the same rated power.

Two other possible disadvantages of a closed-cycle engine must be considered. The heat source heat exchanger places an upper limit on turbine-inlet temperature, and the size and power requirements of the inventory-adjustment system could be prohibitive if the engine is controlled in this way to meet rapid power changes.

For these reasons a semiclosed Brayton cycle might be of interest. The semiclosed Brayton cycle is a compromise between the closed and open cycles. Combustion gases are used as the working fluid, and most of them are recirculated to the combustor to serve as a diluent. Fuel and air are compressed and introduced into the combustor in near-stoichiometric proportions. Because a heat source heat exchanger is not a requirement for the semiclosed cycle, the limitation on turbine-inlet temperature is comparable to an open cycle. Unlike the closed cycle, the semiclosed cycle does not require a separate inventory adjustment system. The open (turbocharging) portion of the cycle pressurizes the system, so control of the open portion is used to control system inventory, hence both flow rate and power level. Because inventory adjustment is used to control power level while maintaining the design-point turbine-inlet temperature, the off-design efficiency variation should be comparable to that of the closed cycle.

Comparison of closed, semiclosed, and open Brayton cycle engines is, in part, a trade-off between off-design performance and engine weight and volume. A detailed analysis is required to quantify these comparisons properly. In addition to engine weight, volume, and design and off-design values of specific fuel consumption (SFC), such factors as complexity, emissions, noise, operational flexibility, cost, growth potential and status of technology must also be considered. A comparison of closed, semiclosed, and open Brayton cycle engines on these bases for applications of interest to the DOT is the primary objective of this study.

Selection of a particular type of engine and design point for a particular vehicle and mission application results from a trade-off involving all of these factors. For each type of engine a wide range of design-point parameters and configurations is possible; therefore, a range of engine weights and design point SFC's can be obtained. Over these ranges some or all of the other factors vary. Therefore, to make the comparisons as general (or valid) as possible, ranges of designs of each type of engine are compared. For example, in the case of the open cycle, designs ranging from highly recuperated to unrecuperated are considered.

Because the study was placed on the more general approach of comparing ranges of designs rather than specific engine designs, the vehicle and mission applications considered were used only as a framework for engine comparisons. Existing vehicle designs were used and were not modified to optimize the engine-vehicle integration. The main emphasis was placed on making a consistent comparison among the types of Brayton engines; less was on comparison either with other types of engines or with other types of motive power such as the wayside power pickup.

The vehicle applications considered are as follows:

(1) An urban bus with one 400-horsepower engine

(2) A 300-mph interurban tracked air cushion vehicle (TACV) with -

   (a) Two 7500-horsepower engines

   (b) Three 5000-horsepower engines

(3) A 150-mph urban TACV with one 5000-horsepower engine

(4) A locomotive with one 5000-horsepower engine

The first two applications were specified by the DOT. The TACV engines supplied a total of 10 000 horsepower maximum net electric power to the linear-induction-motor (LIM) drives and 5000-horsepower net electric power to the levitation fans and TACV auxiliaries. The fuels considered ranged from typical hydrocarbons (kerosene) to cryogenically tanked methane and hydrogen.

The study was divided into two phases. In the first, the engine screening phase, closed and semiclosed cycle Brayton engines were compared. A preliminary cycle screening analysis was used to reduce the number of cycle variations considered. The remaining candidates were then analyzed in more detail and quantitatively compared on the basis of design-point performance, weight and volume, emissions, and noise. Qualitative comparisons were made on the basis of the status of the technology and growth potential.

At the conclusion of the first phase, a semiclosed cycle was selected for further analysis and comparison with an open-cycle Brayton engine in the second phase. In the second or conceptual design phase a more detailed consideration was given to engine performance over various driving cycles and to engine layout and integration into the vehicle. The analysis and results of both phases are given in detail in volume II of this report and are summarized in volume I. Additional studies concerning the production, distribution, cost, and safety of methane and hydrogen fuels and concerning their onboard tankage requirements were performed. These are included in volume II of this report.

1. PROCEDURES

General Approach

The general approach used is indicated in the flow diagram in figure 1-1.

ENGINE CYCLE GROUPS

The thermodynamic cycles were divided into five groups. They are listed in table 1-1.

Groups I and II are closed Brayton cycles which differ in the type of combustion loop used. The cycle schematics of the closed Brayton and its combustion loops are shown in figures 1-2 and 1-3. Group I engines include a combustion loop using a conventional combustor with gaseous diluent. The engines that use excess air as the diluent are referred to as group Ia, and those that use recirculated combustion gas are referred to as group Ib. In group II engines the combustor and heat-source heat exchanger are integrated as shown in figure 1-3(c). Heat transfer from the combustion zone to the Brayton cycle working fluid is used to control combustion temperature, thus permitting near stoichiometric fuel-air mixtures to be used.

The semiclosed Brayton cycle engines considered were designated as group III and are shown in figure 1-4. In this case combustion gas is used as the Brayton working fluid and most of it is recirculated back to the combustor to serve as a diluent. The flow path of the recirculated gas is similar to that of the working fluid in a closed cycle except that it is heated directly in the combustor rather than in a heat-source heat exchanger. The combustion gases that are not recirculated are expanded in an exhaust turbine, which provides power for the combustor-inlet air compressor. The fuel and air input to the combustor (in near stoichiometric proportions) and the combustion gases that are not recirculated have a flow path similar to an open-cycle Brayton. The open part

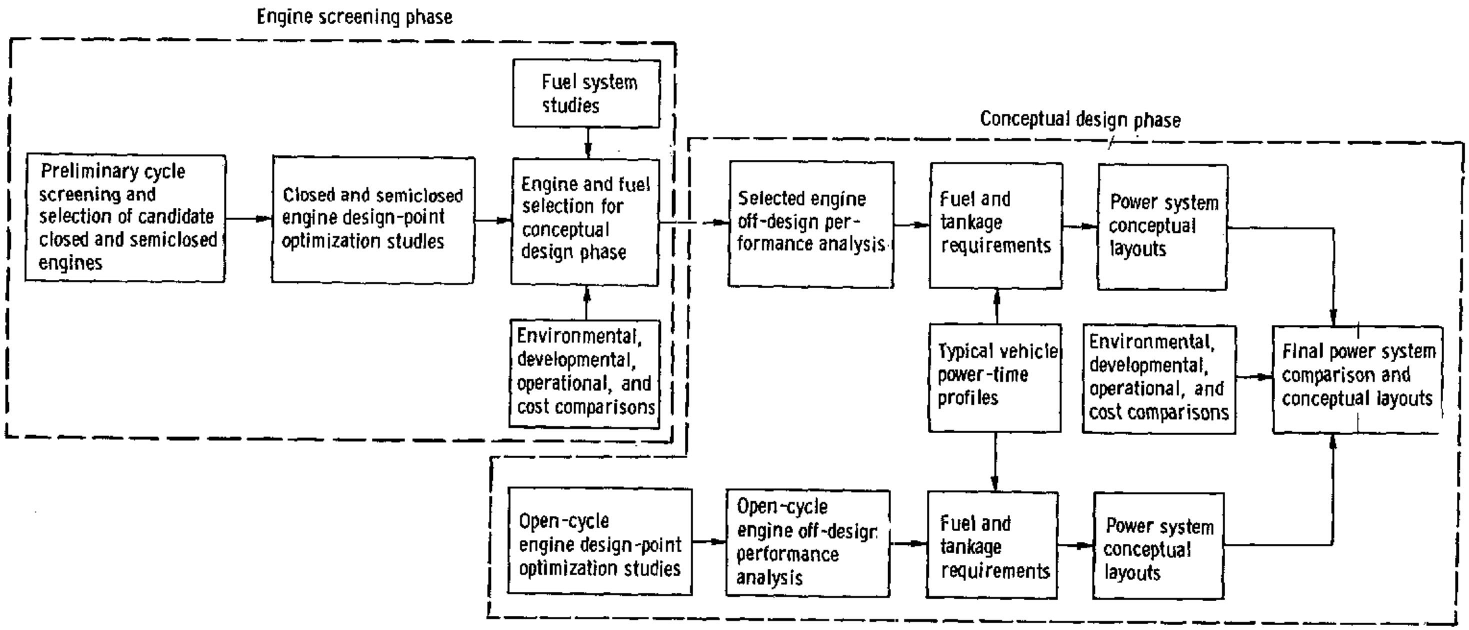


Figure 1-1. - Study flow diagram.

TABLE 1-1. - ENGINES CONSIDERED IN STUDY

Engine designation	Engine description
Group I	Closed Brayton cycle - diluent controlled combustor exit temperature
Ia	Excess air diluent
Ib	Recirculated combustion products diluent
Group II	Closed Brayton cycle - combustion temperature controlled by heat transfer in combined surface combustor and heat-source heat exchanger; near stoichiometric fuel-air ratio
Group III	Semiclosed Brayton cycle - recirculated combustion products as working fluid and pressurized by turbocharged combustion air; near stoichiometric fuel-air ratio
Group IV	Similar to group III, except hydrogen and oxygen are reactants with steam as working fluid
Group V	Open Brayton cycle

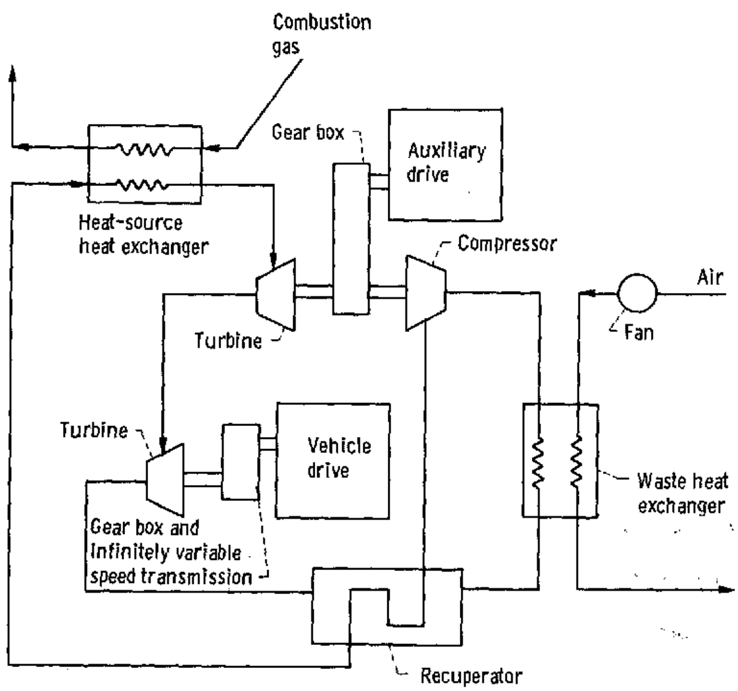
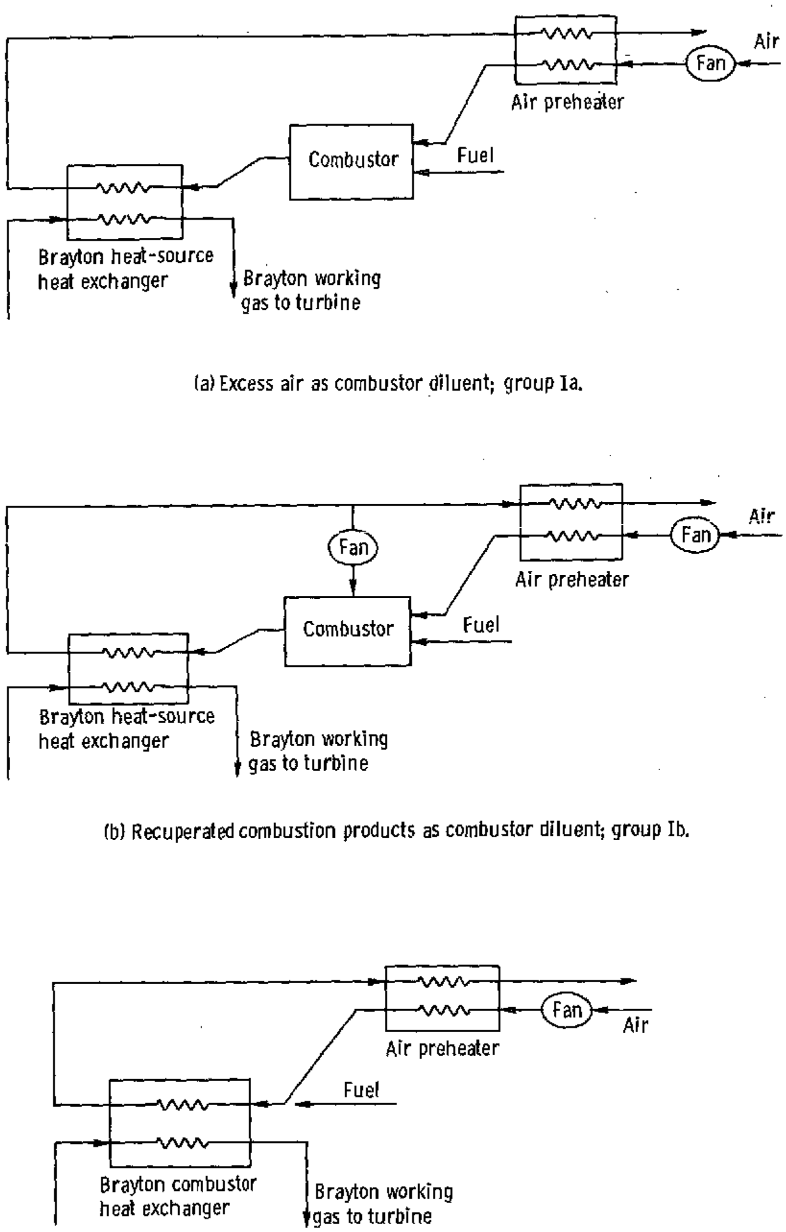


Figure 1-2. - Basic closed Brayton cycle schematic; groups I and II. (IVS denotes infinitely variable speed.)



(a) Excess air as combustor diluent; group Ia.

(b) Recuperated combustion products as combustor diluent; group Ib.

(c) Combined combustor and heat-source heat exchanger; group II.

Figure 1-3. - Combustion loop schematics for closed Brayton cycles.

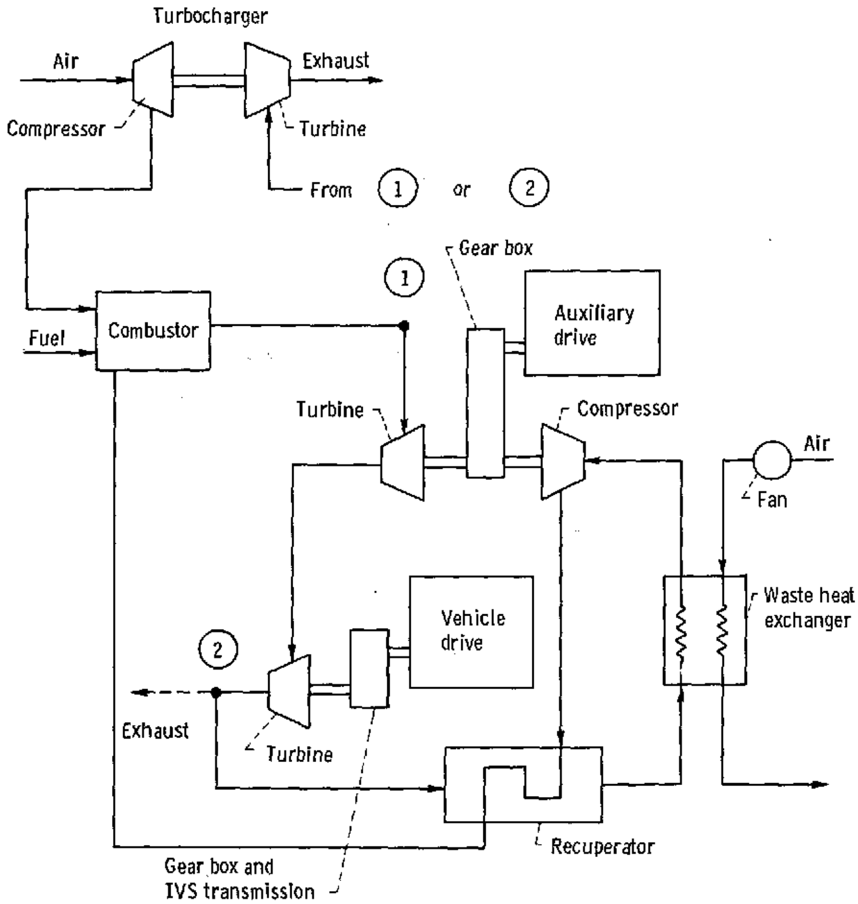


Figure 1-4. - Semiclosed Brayton cycle schematic; group III.

of the cycle acts as a turbocharger to pressurize the closed part of the cycle. Control of the turbocharger serves to control system inventory; hence, the mass flow and power level.

Group IV (fig. 1-5) is a special case of the semiclosed-cycle engine using hydrogen fuel and pure oxygen. Here the recirculated combustion gases are condensed and returned to the combustor as water. The waste heat exchanger and compressor of the Brayton engine are replaced by a condenser and pump in this cycle. Because this hydrogen-oxygen cycle differs so much from the other semiclosed cycles, it was treated as a separate group.

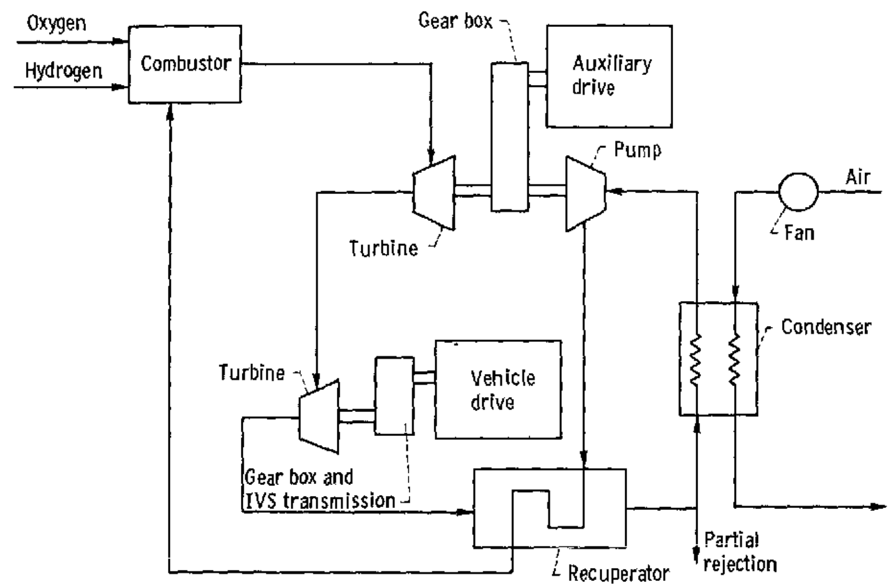


Figure 1-5. - Semiclosed hydrogen-oxygen engine schematic; group IV.

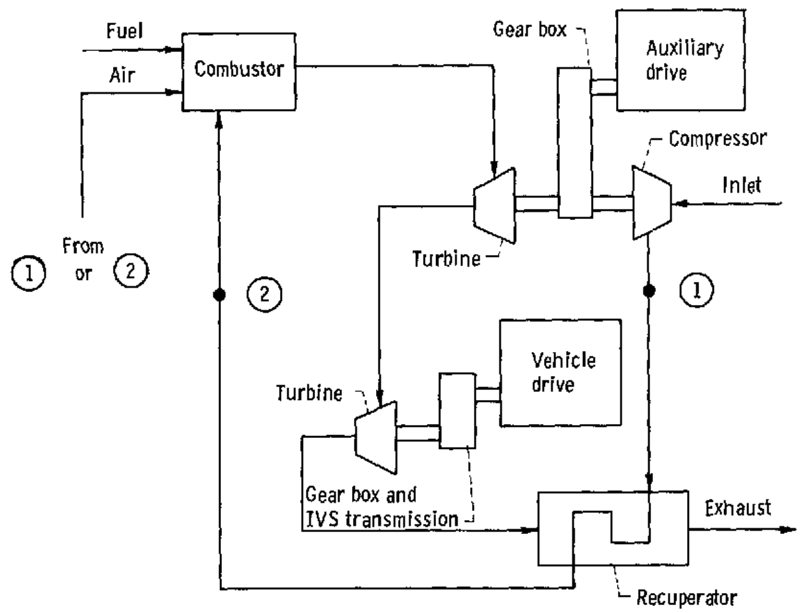


Figure 1-6. - Open Brayton cycle schematic; group V.

The open-cycle Brayton engine shown in figure 1-6 was designated as group V. This engine was considered in the second phase of the study, where it was compared with the group III engine selected at the end of the engine screening phase. The degree of engine recuperation was varied from highly recuperated to unrecuperated.

ENGINE SCREENING PHASE

As shown in figure 1-1 the engine screening phase comparisons between the performance of closed and semiclosed engine cycles (groups I to IV) were made on the basis of design point specific fuel consumption (SFC). For these engines the variation in SFC with power from the design point is very similar. Therefore, the trade-off between performance and engine weight may be illustrated by curves of design point SFC as a function of optimum engine weight. The calculation of those curves is discussed in the section Technical Approach. These engines were also compared on the basis of noise and emissions with qualitative consideration of complexity, cost, technology status, and growth potential.

Several vehicle applications were considered for purposes of comparing these engines. In the engine screening phase, engines from groups I, II, and III were sized at 400 horsepower for the bus application and at 7500 horsepower for the 300-mph TACV application. The group IV engine was considered only for the TACV application. In all cases, to obtain good off-design power level performance, the use of an infinitely variable speed (IVS) transmission was assumed to allow the engine speed to be independent of the load and speed requirements. This transmission is indicated in the cycle schematics.

A number of variations of each engine type were studied. These variations included the use of one- and two-shaft engines, use of reheat or intercooling, and use of turbine cooling. Reheat was dropped early in the study because cycle studies (vol. II, app. I) indicated only marginal benefits. For the bus application, simplicity, compactness, and cost were considered to be the more important. For this reason bus configurations were limited to one-shaft engines. No intercooling was used, and turbine-inlet temperatures were limited to values attainable without the use of turbine cooling. Methane was used as the reference fuel for SFC calculations (except for group IV), but for the engine comparisons made, any other fuel would have served equally well.

CONCEPTUAL DESIGN PHASE

As shown in figure 1-1, in the conceptual design phase, the engine selected from the engine screening phase (group III) was examined in more detail and compared with an open-cycle Brayton engine (group V). Because the off-design-point variation in SFC of the open-cycle engine was expected to vary more than that of the closed or semiclosed-cycle engines, off-design performance was quantitatively evaluated and included in the performance comparison. This was done by comparing the engines on the basis of fuel required for a variety of missions, rather than making the comparisons on the basis of design-point SFC as was done in the engine screening phase.

In addition to the urban bus and 300-mph TACV applications, a 150-mph urban TACV and a present-day locomotive were considered. Both of these applications assumed a 5000 horsepower engine. Two versions of the 300-mph TACV were considered. The first used two 7500-horsepower one-shaft engines coupled to infinitely variable speed transmissions to produce the required 15 000 horsepower net electric power. The transmission for each engine had two output shafts operating at independently variable speed ratios. One output shaft operated at constant speed to drive the alternator supplying the levitation fan, train auxiliary, and engine cooling fan loads. The other shaft drove the alternator supplying the LIM power at speeds determined by the vehicle speed requirements. Engine speed could be varied independently to provide good partial load performance. The second version used three engines, two to drive 5000-horsepower LIM drive alternators through infinitely variable speed transmissions and a third, operating through a fixed-ratio gear box, to drive a 5000-horsepower alternator for the levitation fans and train auxiliaries.

As in the first phase of the study the engine comparisons included consideration of emissions, noise, complexity, cost, growth potential, and the status of the technology. Also, engine compartment layouts were prepared to show the flexibility or limitations of integrating each of the engines into the vehicles.

Technical Approach

DESIGN - POINT ANALYSIS

Design-point performance of the various engines was obtained through the use of design-point power-system optimization computer programs (PSOP). These programs permitted as many as 40 engine parameters to be varied. By optimizing a figure of merit, which is a function of SFC and engine specific weight, and by varying the weighting factor of each design point, performance versus weight trade-off curves were calculated for each configuration of each type of engine. These are curves on which each point represents an engine design with all parameters adjusted to yield minimum engine weight at that particular design-point SFC. They were used in the engine screening phase to compare the engine weight and performance of the engines in groups I to IV. In the conceptual design phase these curves were used with the results of engine off-design-point performance analyses to compare the engines of groups III and V.

Table 1-2 presents the general assumptions and constraints that were used in the engine screening phase. The engine optimizations were constrained so that the airflow frontal area of the waste heat exchangers did not exceed the dimensions shown in the table. This was necessary because the unconstrained optimization resulted in very large airflow areas and heat-exchanger dimensions that could not be integrated into vehicle engine compartments. These constraints were based on available engine compartment size as discussed in appendix F of volume II. Their influence on the engine performance optimizations is discussed in section 7 of volume II.

The design-point assumptions used in the conceptual design phase are given in table 1-3. The footnoted entries indicate changes from the assumptions used in the engine screening phase.

MISSION PERFORMANCE EVALUATION

In the conceptual design phase, several engine design points for each type of engine were selected from the design-point-SFC - engine-weight-trade-off curves. These engine design points were input to the off-design-point perform-

TABLE 1-2. - DESIGN-POINT ASSUMPTIONS AND

CONSTRAINTS - ENGINE SCREENING PHASE

(a) Power system configuration

	Vehicle	
	Bus	Train
Power output, hp	[a]400	[b]7500
Type of turbomachinery	Radial flow	Axial flow
Turbomachinery shaft arrangement	Single	Double
Fuel tank energy capacity, engine output in hp-hr	1500	18 000
Waste-heat-exchanger airflow frontal area, ft	2 by 4	9 by 18
Ambient temperature, $^{\circ}F$	80	80

(b) Engine losses and efficiencies

	Vehicle	
	Bus	Train
Turbine polytropic efficiency	0.87	0.89
Compressor polytropic efficiency	0.86	0.87
Alternator electromagnetic efficiency	0.93 - 0.945	0.93 - 0.945
Thermal losses, percent	5	5
Mechanical shaft losses, percent	5	5
Fan efficiency	0.85	0.85
Fan-drive efficiency	0.98	0.90

[a]Shaft power.
[b]Electric power.

TABLE 1-3. - DESIGN-POINT ASSUMPTIONS - CONCEPTUAL

DESIGN PHASE

(a) Power system configuration

	Vehicle		
	Bus	Train	
Power output, hp	400	7500	[a]5000
Type of turbomachinery:			
Compressor	Radial	Axial	Axial
Turbine	Axial[a]	Axial	Axial
Turbomachinery shaft arrangement	Single	Single[a]	Double
Fuel tank energy capacity	Mission dependent		
Waste-heat exchanger airflow frontal area, ft	2 by 4	9 by 18	9 by 18
Ambient temperature, ^{o}F	80	80	80

(b) Engine losses and efficiencies

	Vehicle	
	Bus	Train
Turbine polytropic efficiency	0.87	[a]0.87
Compressor polytropic efficiency	Modelled[a]	0.87
Alternator electromagnetic efficiency	0.93 - 0.945	0.93 - 0.945
Thermal losses, percent	5	5
Mechanical shaft losses, percent	5	5
Fan efficiency	0.85	0.85
Fan-drive efficiency	0.98	0.90

[a]Changed from engine screening phase assumptions.

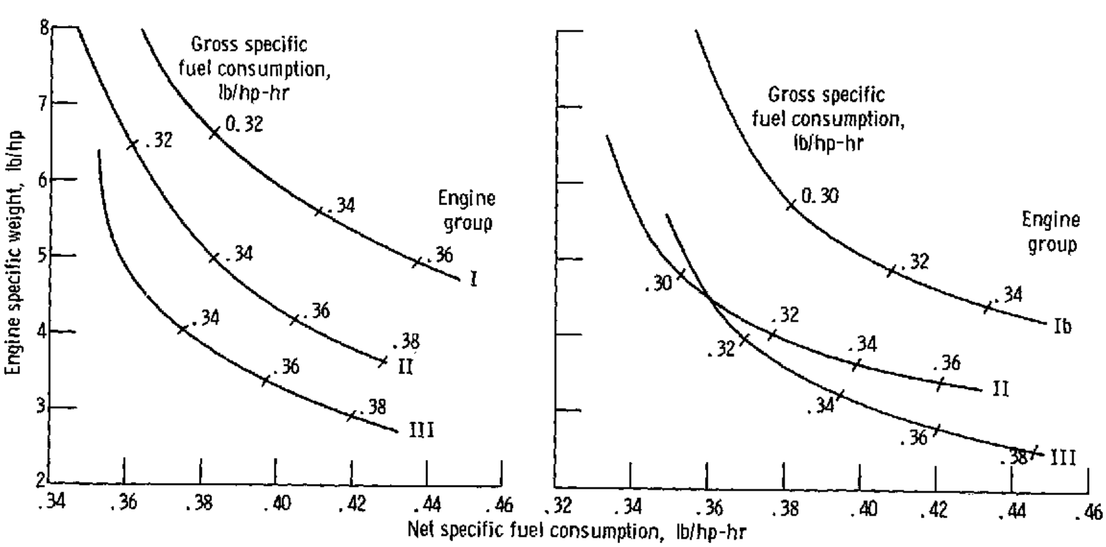
ance computer programs. The resultant engine SFC variations with power, together with transmission efficiencies and mission power-time profiles, were used to calculate the amount of fuel required for a variety of missions. The fuel requirements were combined with required tank weight and engine weight to produce trade-off curves of total system specific weight versus total fuel expenditure for each type of engine and for each mission. Each point on these curves represents a power system with design parameters optimized to result in minimum total power system weight for that particular fuel load.

2. RESULTS

Engine Screening Phase

WEIGHT AND PERFORMANCE

The optimum-engine-weight - design-point performance curves for the basic engines of groups I to III are presented in figure 2-1 for the 400-horsepower bus and the 7500-horsepower train engine. Cycle parameters such as pressure ratio, heat-exchanger effectivenesses, and pressure-loss distribution have been optimized to obtain minimum engine weight at each value of net SFC. In general, recuperator effectiveness decreases, while cycle pressure ratio and pressure losses increase along these curves as the design point SFC



(a) For 400-horsepower bus engines. (b) For 7500-horsepower train engines.

Figure 2-1. - Comparison of basic Brayton cycle engine group performance. Fuel, methane.

is increased. (See vol. II, sec. 4 for details.) These results are for a 1700° F turbine-inlet temperature for the semiclosed cycle and a 1500° F turbine-inlet temperature for the closed cycles. This corresponds to a 1700° F combustor-exit temperature in all cases. The fuel used was methane. Intercooling was not included in these cases. For the closed cycles air was the working fluid. Of the two types of combustor loops in group I, only the results for group Ib are shown. Comparisons between groups Ia and b engines indicated that group Ib was always lighter than group Ia primarily because of the larger preheater required for the group Ia engine.

Maximum cycle pressures for the bus engines (fig. 2-1(a)) were limited to approximately 300 psia for all groups in the engine screening phase. This pressure level was set as a compromise between the advantages of high-pressure levels, which allow more compact equipment, and lower pressure levels, which favor more nearly optimum specific speeds for the radial flow turbomachinery at the 400-horsepower level.

Differences in specific weight among the three types of engine are due primarily to differences in the weight of the combustion-loop components. The combustion-loop weight of the closed cycles is substantially higher than that of the pressurized combustor of the group III engines. The closed-cycle combustion loops operate at atmospheric pressure and require an additional air preheater and for group I a separate heat-source heat exchanger.

The fan power requirements are also more favorable for the group III engine. Differences in fan power among the engines are indicated by the differences between the gross SFC marked on the curves and the net SFC at that point. The group III engine, with no requirement for a separate circulating fan in the combustion loop, has the lowest fan power. A lower combustion airflow in group II, due to near stoichiometric proportions of fuel and air, results in lower required fan power than that of group Ib.

For the 7500-horsepower train engine (fig. 2-1(b)) there was a substantial difference in the cycle pressure level between the closed cycles and group III. For the closed-cycle engines a compressor discharge pressure of 800 psia was assumed to be a reasonable maximum pressure for this application. Limitations related to turbomachinery minimum size and specific speed were not a problem in this application because of the higher power level and use of axial

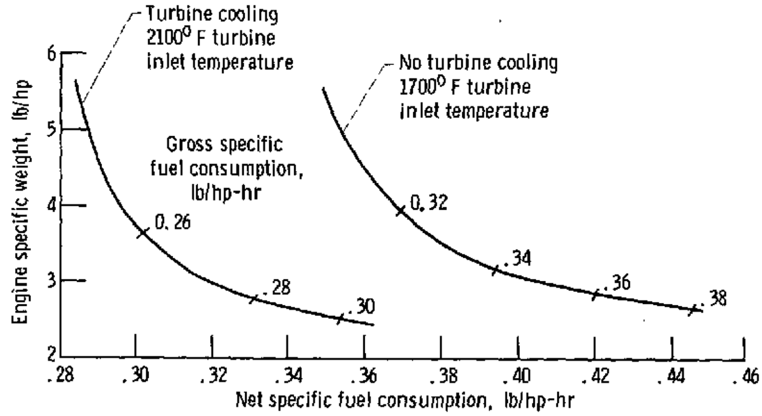


Figure 2-2. - Effects of turbine cooling on group III train engine performance. Fuel, methane.

flow turbomachinery. The maximum cycle pressure of the semiclosed, group III engine, however, was restricted to about 390 psia because of a practical limitation of 25 placed on the turbocharger pressure ratio. As a result of this advantage in cycle pressure level, the performance curve of the group II train engine is much closer to that of the group III engine than was that of the bus engine.

As noted previously, the group III semiclosed engine is similar to an open cycle in that energy is added directly to the working fluid, rather than through the walls of a heat exchanger with its attendant materials problems. For this reason higher turbine-inlet temperatures may be considered for the group III engine if provisions are made for cooling the turbine with compressor bleed gas. Figure 2-2 shows the effect on the performance of the group III train engine of increasing the turbine-inlet temperature from 1700° F without cooling to 2100° F with turbine cooling. A significant improvement in performance is obtained. The method used in calculating the compressor bleed requirements for cooling purposes and its influence on the cycle efficiency are discussed in appendix B of volume II.

Table 2-1 lists the main effects of intercooling between compressors on group II train engines for equal figures of merit. Because of limitations on available engine compartment sizes, the waste heat exchangers both with and without intercooling were constrained to a cooling-airflow frontal area of 9 by

TABLE 2-1. - EFFECTS OF INTERCOOLING ON

GROUP II TRAIN ENGINES

[Fuel, methane; working gas, air.]

	Intercooling	
	Without	With
Total waste heat exchanger length, ft	18	18
Compressor pressure ratio	3.9	6.2
Gross specific fuel consumption, lb/hp-hr	0.357	0.312
Net specific fuel consumption, lb/hp-hr	0.389	0.403
Gross shaft power, hp	8800	9700
Power losses, hp:		
Total	1300	2200
Shaft	950	1050
Fan	350	1150
Initial weight estimates, lb:		
Total	45 200	45 600
Tank and fuel	17 050	17 900
Engine	28 150	27 700

TABLE 2-2. - EFFECTS OF INTERCOOLING ON

GROUP III TRAIN ENGINES

[Fuel, methane.]

	Intercooling	
	Without	With
Total waste heat exchanger length, ft	18	18
Compressor pressure ratio	4.3	6.8
Gross specific fuel consumption. lb/hp-hr	0.324	0.303
Net specific fuel consumption	0.374	0.354
Power losses, hp:		
Total	1160	1270
Shaft	890	900
Fan	270	370
Initial weight estimates, lb:		
Total	43 400	41 700
Tank and fuel	15 200	14 300
Engine	28 200	27 400

18 feet. With intercooling, the gross SFC was lower, but the fan power requirement tripled. As a result, the group II engine performance was poorer with intercooling than without under the constraints imposed by available flow area for cooling air.

The effects of intercooling on group III train engines for equal figures of merit are listed in table 2-2. A total waste-heat-exchanger cooling-airflow area constraint of 9 by 18 feet was imposed for each case. Although fan power requirements increased by 100 horsepower, intercooling showed a decrease in net SFC of about 6 percent. Thus, although intercooling complicates engine arrangement, there are some potential benefits for its use with the semiclosed Brayton cycle engines.

Air and mixtures of helium and argon were considered as working fluids for the closed cycles. Although the use of xenon or krypton mixed with helium would provide superior gas mixtures, they were not considered for these applications because of their costs and limited availability. At the molecular weight of air, a mixture of helium and argon showed no advantage over air as a working fluid from the standpoint of engine specific weight. Small engine weight savings were possible at molecular weights less than air, but the required number of turbomachinery stages became large. Air was, therefore, selected as the closed cycle working fluid for bus and train applications.

The comparisons of the groups in figure 2-1 were not significantly affected by the use of either kerosene or hydrogen fuel rather than methane. However, the total system weight including fuel and tankage is affected. More fuel weight is required for kerosene because of its lower heating value. The conventional tankage for kerosene is much smaller and lighter than the cryogenic tankage required for methane and hydrogen. This is illustrated by the results in appendix I of volume II.

The group IV semiclosed hydrogen-oxygen engine is unique among the cycles studied in that both the fuel and the oxidant must be carried. As a result, the rate of consumption of the consumables, expressed as specific reactant consumption is substantially higher than the specific fuel consumption (SFC) of the other engines using air as the oxidant. The weight of the fuel, oxidant, and tankage dominated system weight and volume, making it unattractive for mobile applications For example, the minimum total system specific weight for the 7500-horsepower train engine was 10 pounds per horsepower at a turbine-inlet temperature and pressure of 1800° F and 600 psia for an 18 000-horsepower-hour mission at design power. Also, the condenser was so large that it was difficult to integrate the engine into the guideline engine compartment. With constraints on the condenser size imposed, system performance was seriously degraded and total system specific weight was substantially increased over the 10-pound-per-horsepower minimum value. On the basis of these considerations, the group IV engine was not considered further in this study.

EXHAUST EMISSIONS AND NOISE

All of the Brayton engines have the potential for low exhaust emissions. Because the combustion is continuous, the design flexibilities available for reducing undesirable emissions are greater than for presently used intermittent combustion engines. The operating conditions imposed on the combustor differs in each of the engine groups; thus the emissions potentials differ. These are quantitatively compared in appendix D of volume II.

The emissions of groups Ia and Ib are similar, with those of group Ib slightly lower because of the use of recirculated combustion products as combustor diluent. Of the closed-cycle engines, group II with its surface combustor has the lowest emissions. The group II surface combustor is integrated with the heat source heat exchanger so that the heat transfer from the combustion zone limits the peak combustion temperature and, hence, the production of oxides of nitrogen (NO_x). The discussions of appendix D in volume II, show that the low emission potential of the surface combustor is substantially better than that of the diluent class of combustors in group I.

The group III engine uses a combustor similar to that of group I except that it operates at the cycle peak pressure rather than near atmospheric pressure as in group I. As discussed in appendix D (vol. II) this would result in higher NO_x emissions for group III. A surface or catalytic combustor could be used with a semiclosed cycle engine and in this way reduce the emissions to near the level possible with the group II engine. But such a combustor would be larger than the diluent controlled type of combustor considered in the analysis.

For the closed Brayton engines the dominant noise sources are those external to the power conversion loop, that is, coolant and combustion air fans, transmission, and alternator. In appendix D it was concluded that these sources could be limited to below 75 decibels A (dBA) at 50 feet at full power for all closed-cycle engines.

In the semiclosed cycles, the turbocharger and the rejection of gas from the pressurized loop present additional noise sources. The turbocharger is similar to an open-cycle turbine and is amenable to the same kind of acoustic treatment as used to quiet current aircraft engines. Ground applications also permit additional noise attenuation to be included in the engine compartment. It was concluded that the group III engine noise may be 5 dBA higher than that for closed cycle engines.

TECHNOLOGY STATUS AND GROWTH POTENTIAL

Closed Brayton systems are in operation in Europe for stationary power applications. To this time, however, they have not been adapted to mobile terrestrial applications. The materials technology of the heat-source heat exchanger limits the turbine-inlet temperature and, hence, the potential performance of the engine. This heat exchanger must be able to withstand the thermal cycle fatigue due to engine startup and shutdown and the substantial pressure difference between sides, as well as the temperature level. In addition, the group II integrated combustion heat exchanger still requires development.

The semiclosed-cycle Brayton engine combines some of the advantages of the closed- and open-cycle engines but apparently has not been reduced to practice. The cycle configuration studied eliminates the need for a heat-source heat exchanger and therefore its limitations on turbine-inlet temperature. However, since combustion products are used as the working fluid, condensation in the waste heat exchanger will require consideration of materials compatibility and a means for water extraction.

The best off-design power level performance of a closed-cycle Brayton is attained when power level is controlled by inventory adjustment. However, a practical scheme for accomplishing inventory adjustment for rapid power transients required by vehicular applications was not established during this study. To the extent that rapid transient response using inventory adjustment is required, control of the closed-cycle Brayton is an unresolved issue. For the semiclosed cycle, control of power level by inventory adjustment can be accomplished by proper control of the turbocharger. The control of this turbocharger requires some development and is discussed in appendix C of volume II.

SELECTION OF ENGINE FOR CONCEPTUAL DESIGN PHASE

Of the closed cycles (groups I and II) the group II engine was superior on the basis of weight, design-point performance, and emissions. Off-design power level performance and noise should be comparable for the two groups. There should be little difference in cost except for the group II combustor, which requires development. On this basis the selection between closed and semiclosed cycles should be a selection between groups II and III.

The criteria considered and the results of the comparison of groups II and III are given in table 2-3. Note that some of these criteria are not by themselves significant factors in the selection of the better engine type.

The group III engine had superior growth potential because the group II turbine-inlet temperatures were limited by the requirement of a heat-source heat exchanger. The multifuel capability of group II was questionable because

TABLE 2-3. - ENGINE COMPARISON SUMMARY - ENGINE SCREENING PHASE

[X indicates the engine with the better performance. When X appears in both columns, no discernible difference was noted. When ? appears, further study is needed to assess performance for the criterion.]

Criteria	Group II	Group III
Low specific fuel consumption and weight		X
Low volume		X
Growth potential		X
Good partial power performance	X	X
Multifuel capability	?	X
Low emissions potential	X	?
Noise	X	
Minimum technology issue	X	X

this aspect of the operation of surface combustors (which group II requires) needs further investigation. Group II's low emission potential (using a surface combustor with near atmospheric pressure combustion) was rated above group III. Group III could also use a surface combustor to significantly reduce the emission levels below that expected from the diluent controlled combustor used in the group III cycle configuration analyzed. But the applicability of the surface combustor to the higher pressure level of the semiclosed-cycle combustor needs further study. From the standpoint of noise, group III poses more of a problem than group II. However, with appropriate acoustic treatment, it should not be a significant factor in choosing between the two groups.

On the basis of the comparisons summarized in table 2-3, the group III engine was selected for further analysis and comparison with the open cycle, group V. The power systems analysis assumed the use of kerosene fuel. The effects of using other fuels on the fuel storage systems are described in appendix H of volume II.

Conceptual Design Phase

WEIGHT AND PERFORMANCE

As in the engine screening phase, the engine design points were optimized for minimum engine weight over a range of design-point SFC. The optimum weights for a range of design points are given in figure 2-3 for engine groups III and V and the three power levels considered. As discussed previously, parameters such as heat exchanger effectiveness, pressure ratio, and pressure losses vary along each of these curves. For both engines the recuperator effectiveness decreases, while the pressure ratio and pressure losses increase as the design-point SFC is increased. (See vol. II, sec. 5 for details.) The group III engine optimization had to be constrained to make the waste-heat exchanger fit the guideline engine compartment dimensions.

Because of the absence of the waste heat exchanger and in spite of the lower pressure level and less dense recuperator core, the open-cycle engine is lighter. Also, the range of design-point SFC is lower for the open-cycle engine because the open cycle has no temperature difference between the com-

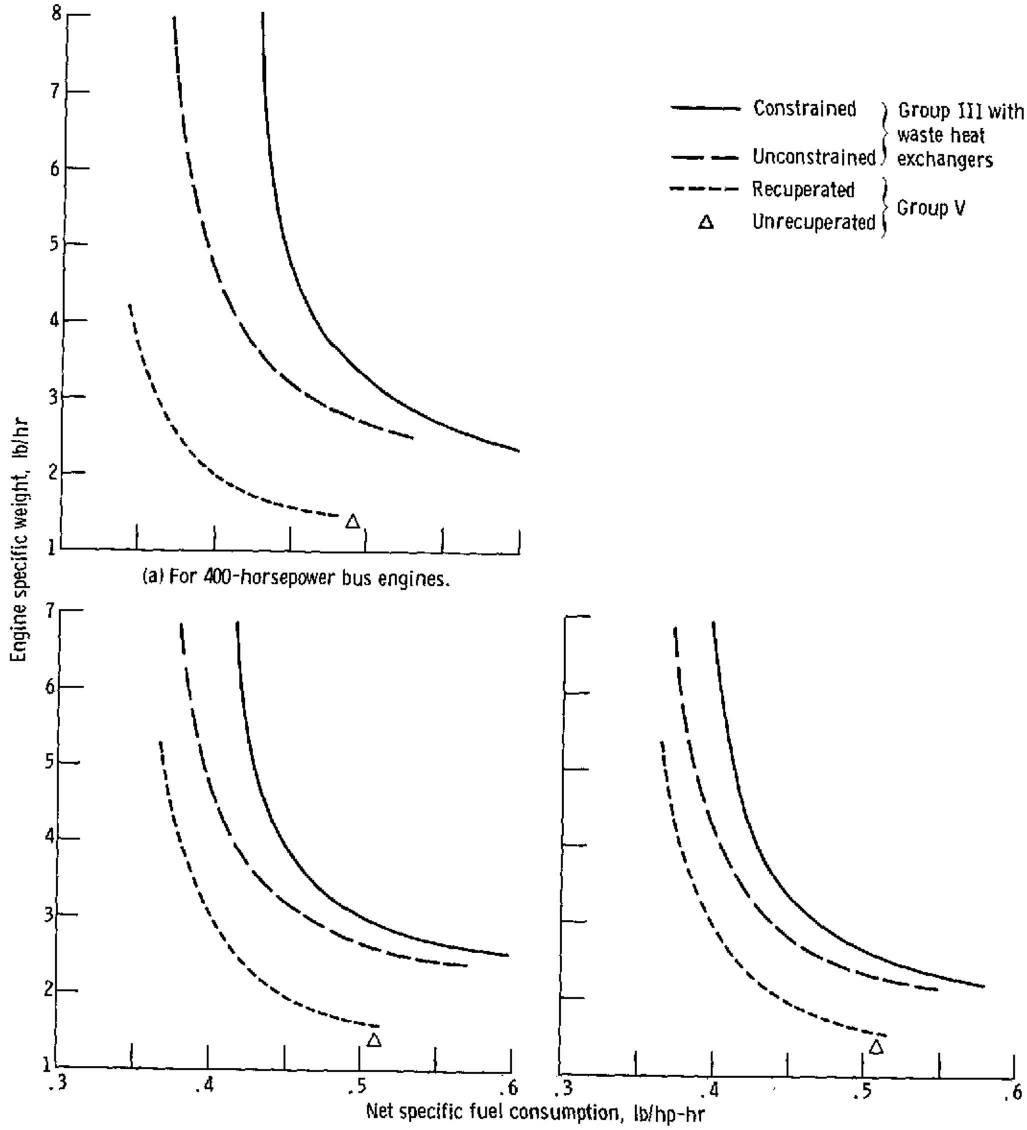


Figure 2-3. - Optimum-weight and design-point performance. Fuel, kerosene; turbine-inlet temperature, 1700° F. Engine weight includes all heat exchangers, turbomachinery, combustor, ducting, and reduction gear box. Net SFC includes effect of losses and parasitics.

pressor inlet and ambient air, does not have to generate power for air coolant fans, and obviously does not have to be constrained.

The curves in figure 2-3 show the trade-off between engine weight and design-point SFC. But for an application where a fixed engine is used over a range of power levels and where the SFC of that engine varies with power output, the design-point SFC does not fully describe engine performance. In the engine screening phase all the engines considered were expected to have a rather small variation in SFC with power output. In that phase, not only is the design-point SFC a good indication of engine performance, but also it is a valid basis on which to compare engines. In the conceptual design phase the open-cycle engine was considered, and its off-design SFC values were expected to vary significantly. Therefore, a complete comparison of the performance of the engine groups III and V would have to quantitatively include the effects of off-design operation. For example, consider the sketch of the off-design variation in SFC for two engines in figure 2-4. A closed or semiclosed cycle might be represented by curve A and an open cycle by curve B. A comparison of design point SFC leads to the conclusion that engine B is more efficient; however, at low power the curves cross and engine A has the lower SFC. A mission application that includes a lot of operation at low power could result in engine A's requiring less fuel and therefore being the more efficient engine. Further, for such a mission, depending on the relative engine and fuel weights,

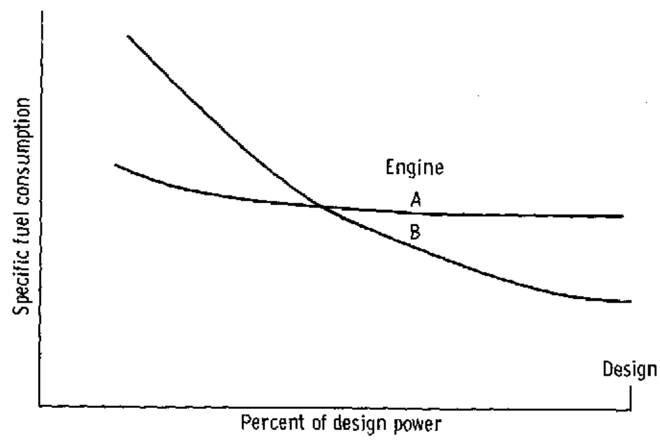
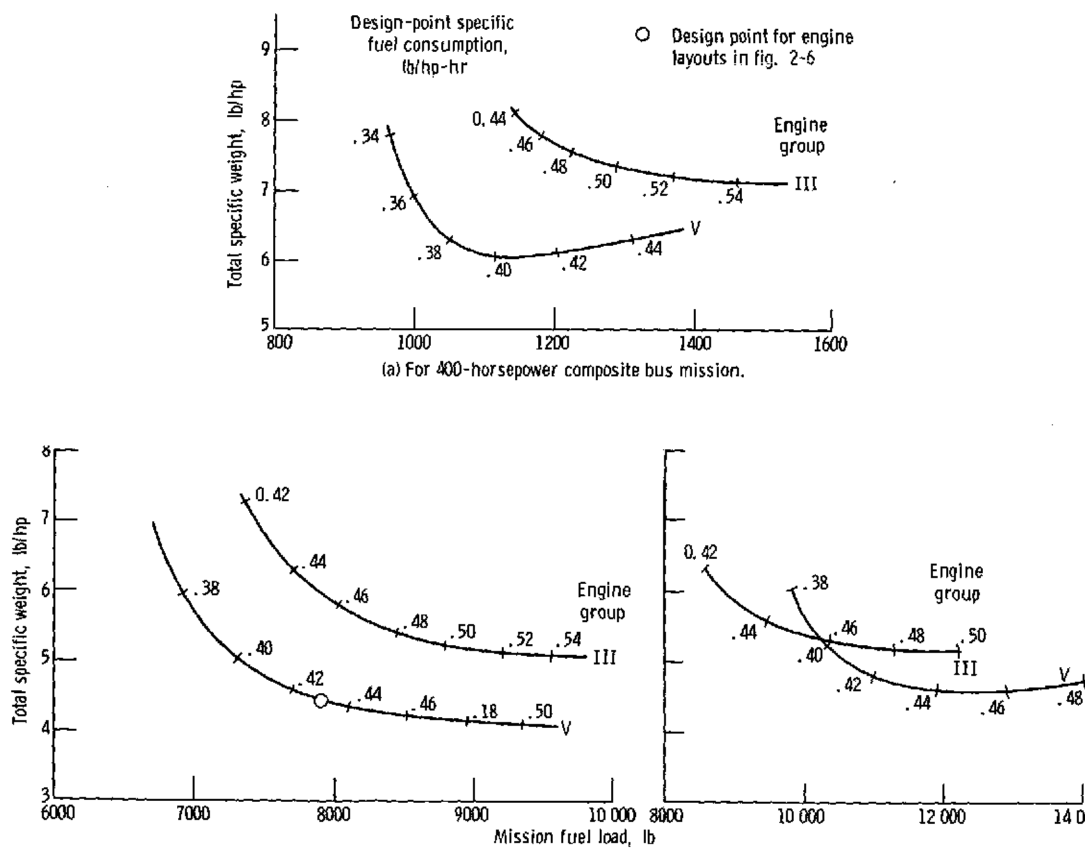


Figure 2-4. - Engine off-design performance.

engine A could result in lower total weight (where total weight includes engine and fuel) even though engine A has the heavier engine. Therefore, to include the effects of mission application and off-design performance, groups III and V are compared on the basis of total power system weight and mission fuel requirements for the missions examined.

In figure 2-5(a) the total weight and the fuel weight required are given for a range of engine designs for groups III and V for a 400-horsepower engine and composite bus mission. Each point on the curves represents an engine design. The fuel requirements for a given design are obtained first by calculating the off-design variation in SFC for that design (as described in vol. II sec. 5) and then by integrating the product of the SFC, transmission efficiency, and engine



(a) For 400-horsepower composite bus mission.

(b) For 7500-horsepower single-shaft TACV engine.

(c) For 5000-horsepower locomotive, including idle.

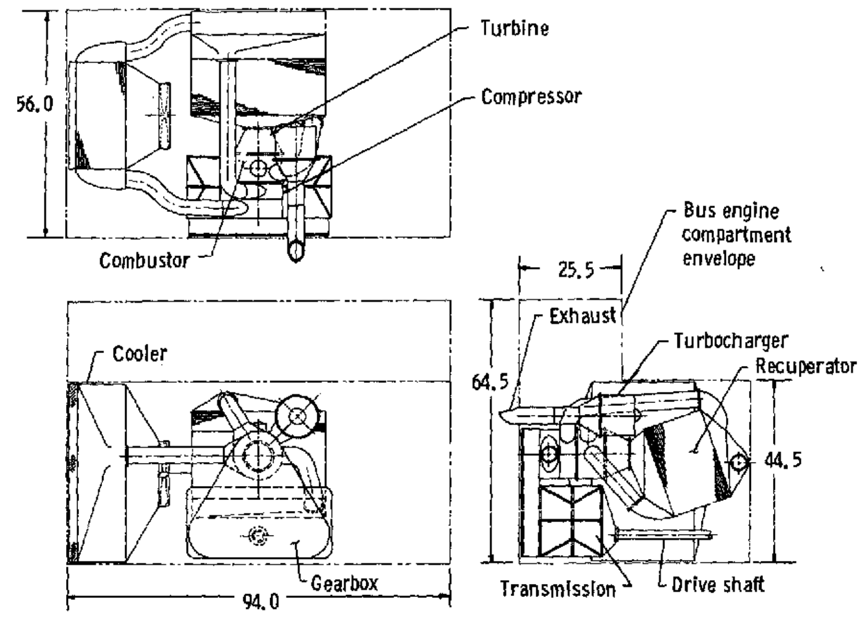
Figure 2-5. - Total system weights (includes engine, transmission, fuel, and tanks).

power output over the time period of the mission (as discussed in vol. II, app. F). The composite bus mission consists of 10 journeys each 10 miles long with maximum acceleration to 50 mph and of 600 journeys each 0.5 mile long with a 0.1 g acceleration to 20 mph. As shown in figure 2-5(a) the group V engine over the range of design points considered is both lighter and more efficient than the group III engine.

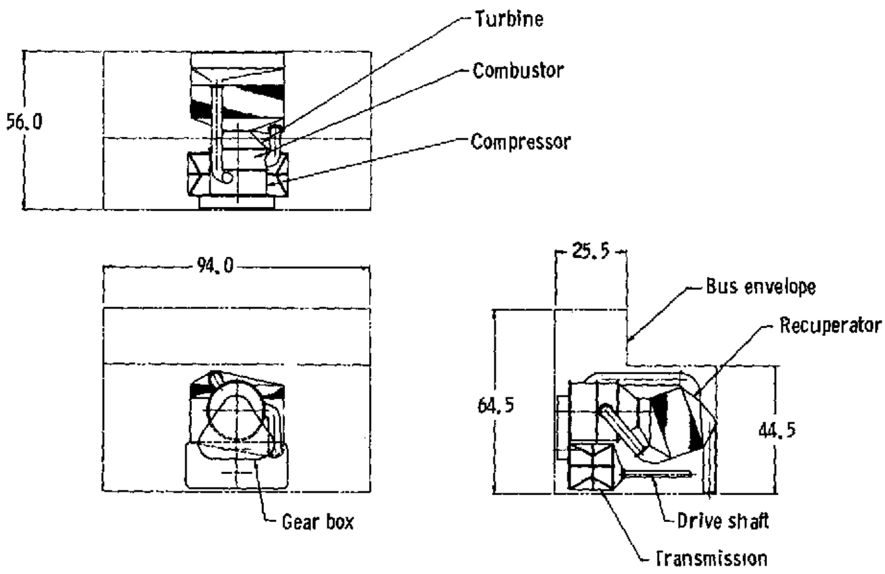
In figure 2-5(b) a 7500-horsepower engine is considered for the 300-mph TACV application. Two such engines would supply thrust power and lift fan power. As in the case of the bus application the group V engine results in lower total weight. A 5000-horsepower engine was considered as one of two thrust power engines for the 300-mph TACV application, and it was considered as an engine supplying both thrust power and lift fan power for a 150-mph urban TACV. For these applications the comparison between the engines of groups III and V was similar to that shown in figure 2-5(b). (The comparisons for these cases are shown in vol. II, sec. 2.)

A locomotive application using a 5000-horsepower two-shaft engine is considered in figure 2-5(b). For this case the engine is assumed to operate at full power for 30 percent of the time, at 30 percent power for 30 percent of the time, and at idle for the remaining 40 percent of the time. (See vol. II, app. F.) For this application the low power operation is so dominant that the better SFC of group III at low power levels results in the total fuel consumption of the group III engine extending to a lower range than is possible with the group V engine. However, in such a case engine shutdown rather than idle for such long periods might be considered, and this would make group V appear more favorable.

As explained previously the group III engine is operated at off-design power levels by changing system pressure level while maintaining constant turbine-inlet temperature and engine speed. To maintain constant engine speed, independent of vehicle requirements, the use of an infinitely variable transmission has been assumed with the group III engine. To facilitate comparison, the use of such a transmission has also been assumed for the group V engine. By allowing the group V single-shaft engine speed to vary independently of vehicle requirements, the turbine-inlet temperature can be held constant. The group V off-design performance is, therefore, much improved over that which

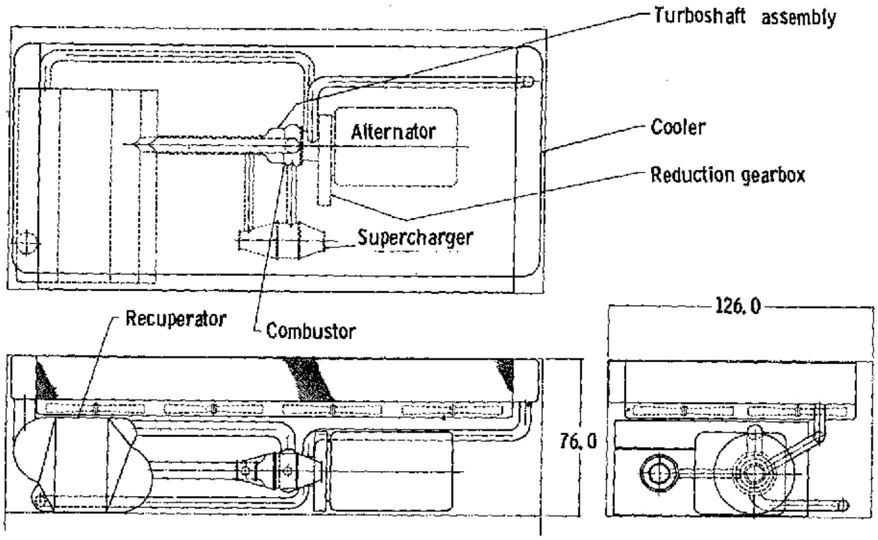


(a) Group III engine.

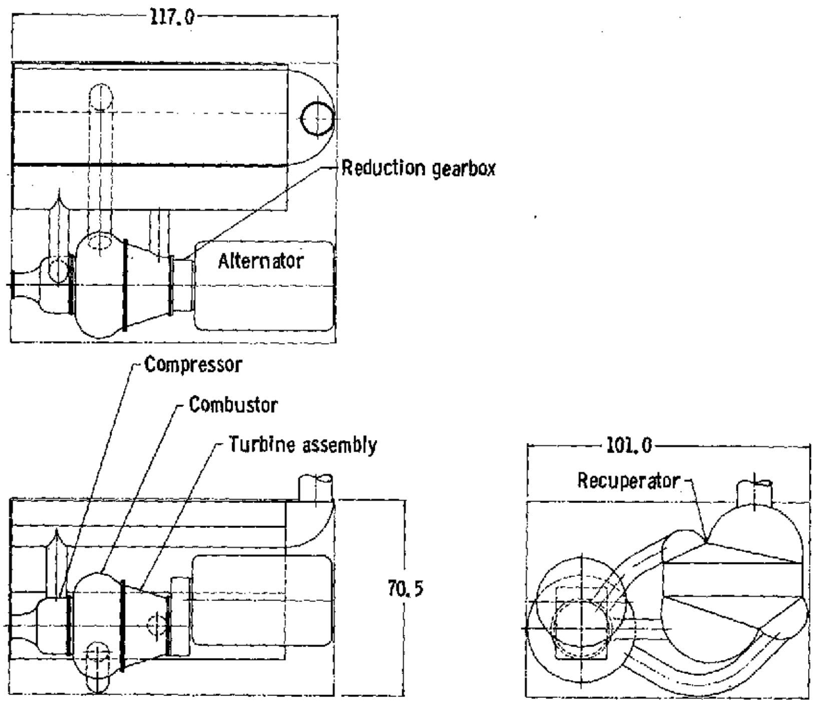


(b) Group V engine.

Figure 2-6. - Conceptual layout of 400-horsepower, single-shaft bus engines. (All dimensions are in inches.)



(a) Group III engine.



(b) Group V engine.

Figure 2-7. - Conceptual layout of 7500-horsepower, single-shaft TACV engines. (All dimensions are in inches.)

is possible when the turbine-inlet temperature is reduced with a reduction in power. In this way the off-design performance approaches that of the semi-closed cycle engine; the comparisons in figures 2-5(a) and (c) do not show as much off-design performance effect as might be expected.

In addition to lower weight, the group V engine, because it has no waste-heat exchanger, is much more flexible with respect to vehicle-engine integration. This is illustrated by the engine compartment configuration for the two engines shown in figure 2-6 for the bus engine and in figure 2-7 for the 300-mph TACV. These engine concepts are for the engine design points indicated by the circle symbols in figures 2-5(a) and (b).

EXHAUST EMISSIONS AND NOISE

The combustor used in the engines of groups III and V are the same type, using a gaseous diluent for temperature control, and both operate at the maximum cycle pressure. The major differences that affect emissions (primarily NO_x emissions) are the pressure level and the combustor-inlet primary air temperature. The group III combustor pressure tends to optimize at higher levels than group V. The combustor primary-air inlet temperatures vary for both engines, from about 800° to 1200° F for the design points of figure 2-3. Considering the effects of both pressure and temperature, the NO_x emissions are predicted to be higher for the group III engine. The hydrocarbons and CO emissions would be comparable. The comparison of the emission potential of these engines is shown in table 2-4. (Group II is included for convenience.)

TABLE 2-4. - EMISSIONS POTENTIAL SUMMARY

[Fuel, kerosene.]

Group	Type of combustor	Emission index, g/kg of fuel		
		HC	CO	NO_x
II	Surface	<1	<10	<1
III	Conventional		<10	<10
	Catalytic		<1	<.5
V	Conventional		<10	<5

Both groups III and V could use a surface or catalytic combustor and emissions would be substantially reduced. Both types of combustor require development; the effects of combustor type on engine weight or performance was not analyzed. However, since both require premixing of the fuel and air, the engine optimizations might have to be constrained to limit the primary-air temperature and avoid auto-ignition. This would be expected to affect the performance of both engines, but it is not expected that this would alter the conclusion that the group V engine is the lighter and the more efficient for these applications.

It appears that both types of engine can be quieted to the guideline acceptable noise levels with about the same amount of acoustic treatment of engine and engine compartment. Noise does not, therefore, appear to be a significant factor in selecting the best engine.

TECHNOLOGY STATUS AND GROWTH POTENTIAL

The group III (semiclosed) engine concept has not been demonstrated. The open-cycle Brayton has a well developed technology. The existing applications of this engine are predominantly of the simple (unrecuperated) open cycle. However, the regenerated (or recuperated) engine has also seen substantial development. The attributes of this engine that have spurred its development are its lightweight and low volume. The major impediments to widespread use in the heavy-duty ground transportation system have been cost and partial-load SFC when compared with the diesel engine. As a result of recent achievements in the automobile industry, predicted costs have been coming down. Also, recent developments in power transmission (i.e., the infinitely variable transmission) offer improved partial-load fuel economy. As discussed previously, this results in fuel economy comparable to that of closed cycles over a broad range of power variation.

ENGINE COMPARISON

The results of the analysis and comparisons presented are summarized in table 2-5. In that table the criteria considered are listed, and engine groups III and V are comparatively rated. (Engine group II is also included for conveni-

TABLE 2-5. - ENGINE COMPARISON SUMMARY - CONCEPTUAL DESIGN PHASE

[X indicates the engine with the best performance. When X appears in more than one column, no discernible difference was noted. When ? appears, further study is needed to assess performance for the criterion.]

Criteria	Group II	Group III	Group V
Low specific fuel consumption and weight			X
Low volume			X
Good transient response			X
Growth potential		X	X
Good partial power performance	X	X	X
Multifuel capability	?	X	X
Low emission potential	X	?	?
Flexibility			X
Noise	X		
Minimum technology issues			X

ence.) Again, some of the individual criteria were not as significant as others in the selection of the best engine.

Additional Considerations

In any study such as this there are inevitably considerations, options, and arrangements that are consciously or unconsciously omitted. It has been the emphasis in this study to insure that first-order effects be treated in sufficient detail to insure the basic validity in the selection process. The assumptions and constraints were uniformly applied to each of the engine concepts. The models for the various components were treated with varying degrees of detail commensurate with the importance of that component to influence selection. As an example, the heat exchangers were unquestionably a major determinant for each system size, weight, and performance (a first-order effect); as a result each of the heat-exchanger models was more detailed than were the ducts and gear boxes (a second-order effect). The comparison of the engines, therefore, has greater validity than the numerical values for each individual engine. However, it was recognized that the study results would also be used to compare the attractiveness of these engines for the various applications with, say, the diesel engine. Therefore, emphasis was placed on insuring that all models were reasonable representations for all components. Sufficient information is provided to permit the reader to judge both emphasis and validity.

As noted earlier, several considerations not deemed to be of first-order importance to engine selection were omitted. Some, however, could amplify the difference between the engine concepts. Some of these are listed here and their effects briefly summarized.

Inventory control - The results shown for the group II engines are optimistic since no allowance has been included for inventory control equipment and power requirements. A more detailed analysis, therefore, would result in a general increase in weight and SFC.

Transmissions - This study treated a wide range of vehicle types with distinctly different load characteristics. The engines perform best not only at constant turbine-inlet temperature but also on a speed-power schedule independent of load. Furthermore, the engines of groups II and III, to be realistically applied, should be constant-speed engines, since mass flow variation by inventory adjustment rather than speed change, is one of their more advantageous characteristics. It seems realistic to exploit this attribute, which then requires the use of a high efficiency, infinitely variable transmission. The state-of-the-art of this transmission is well established and commercially available at a power of several hundred horsepower. A survey of manufacturers of this type of equipment was made during this study, and no question of basic feasibility at power levels to 7500 horsepower was discovered; however, development and demonstration would be required at these higher power levels. The assumed use of this transmission for all the engines permitted engine speed variation for best fuel consumption independent of load requirements and also provided a uniform basis of comparison for the various types of engine. It is important to recognize that this is an important assumption for all the engines studied, but in particular for the group V engine. This feature permitted the engine to be operated off-design at constant turbine-inlet temperature, which then accounts for the partial-power performance of group V so closely approximating both groups II and III.

Alternative working gases - The group II engine is capable of utilizing working fluids other than air. Low-molecular-weight inert-gas mixtures of helium and argon were evaluated (vol. II, sec. 7) and did not appear advantageous. Heavier than air molecular weights, such as a mixture of helium and xenon, were not examined. Although such mixtures yield better heat transfer and turbomachinery performance, they were omitted because of their cost and limited availability. In addition, the major benefit of using helium-xenon mixtures would be in the recuperator, with little effect on the heat source and waste-heat exchangers, which are combustion side and ambient air side limited on heat transfer, respectively. Although more detailed analysis is required to quantify the comparison, it does not appear to be a fruitful approach.

Pressurized combustion loop - The combustion side of the group II heat source could be pressurized with a turbocharger. The use of a turbocharger could markedly reduce its size. This could be an attractive approach, but does not ameliorate the major group II problems, that is, heat-source - heat-exchanger temperature limits, inventory control, and waste-heat exchanger size. The conclusion is that this feature would not significantly affect the study comparison results.

Turbine water cooling, water injection, and variable geometry - These three factors apply to groups III and V and are lumped together, not because they are related to each other, but because the effects, if treated, would amplify the advantages of these groups over group II. Water cooling technology has been developed but not applied. Its advantage lies in permitting higher turbine-inlet temperature without compressor bleed penalty to the system. Variable geometry, on the other hand, is current commercial practice, its use can be well justified and should be treated in any more detailed study. Water injection was not treated in engine performance, but it could significantly reduce NO_x emissions. It is expected that its effect on performance would also be advantageous and should also be included in any more detailed engine definition study.

Engine design-point selection and turbine-inlet temperature - In all cases, design-point optimization was done for maximum power. It would appear advantageous to choose a design point nearer to average power levels and trade improved low end SFC against some penalty at full power for those applications dominated by partial power operation. Another feature that could be combined with this approach would be the exploitation of higher turbine-inlet temperature for maximum or high power operation for short periods of time with sustained temperature operation limited to say 1700° F. Had these techniques been studied, the performance of groups III and V would have benefited. It is difficult to estimate the quantitative improvement without detailed analysis of these approaches.

Group III engine variants - The group III engine considered in this study is only one example of the semiclosed type of Brayton cycle. Many other variations are possible, some of which are described in section 6. It cannot be said that the group III engine studied is the best of the semiclosed engines, but the results should be tvpical and the conclusions valid.

3. CONCLUSIONS

All of the Brayton engines considered are thermodynamically similar. The differences are in the way heat is added to the working fluid (directly with combustor in the gas loop or indirectly with a separate combustion loop), in the way heat is rejected (direct exhaust of the working fluid or indirect by means of a waste heat exchanger), and in the way power level is changed. These differences affect such engine characteristics as weight, volume, design-point and off-design power level SFC, noise, emissions, cost, complexity, flexibility, growth potential, and technology status. Each of the types of Brayton cycles considered have distinct advantages and disadvantages, depending on the application. As mentioned in the INTRODUCTION the selection of one of these types of engine for a particular application involves a trade-off among some or all of these characteristics.

The comparison of closed (group II), semiclosed (group III), and open (group V) cycle Brayton engines for the applications considered are summarized in table 2-5. These comparisons and the selection these engine types for a particular application are discussed in this section.

When waste heat is rejected to the atmosphere, the closed and semiclosed systems suffer a penalty in design-point SFC, size, and weight because of the waste heat exchanger. Increasing the system pressure level does not substantially reduce the size of this heat exchanger since its size is air-side heat-transfer controlled. In addition, for mobile applications where constraints must be placed on overall dimensions, system performance is further penalized.

Comparing the open-cycle engines with the semiclosed and closed cycle engines showed the open cycle to be lighter at the same design-point SFC or to have a lower design-point SFC at the same engine weight. However, the valid comparison of these engines must include the effects of off-design-power-level operation. The lower design-point SFC and weight of the open cycle might be offset by the effects of higher off-design-power-level SFC and consequently higher required fuel loads.

In comparing closed and semiclosed engines, this is not as significant a factor since the variation in SFC of these engines when inventory adjustment control is used is relatively small. And design point SFC is a good measure of engine performance on an actual mission. To include the off-design power level effects, comparisons between groups III and V were made on the basis of total fuel expended for several different missions and total system weight, including engine, tankage, and fuel.

To obtain the best off-design performance with a semiclosed or closed Brayton, inventory adjustment is used to control power level while maintaining constant engine speed and turbine-inlet temperature. To maintain constant engine speed, independent of vehicle speed, an infinitely variable speed (IVS) transmission is required. Since it is needed for the other cycles, it has also been used in the open-cycle engine analyses to allow comparisons to be made on an equal basis. Use of the IVS transmission allows the single-shaft open-cycle engine speed to be varied in such a manner that turbine-inlet temperature remains constant over a wide range of power levels. This results in an off-design performance for the recuperated open cycle, that is much better than that obtained without use of the IVS transmission.

For the mission applications considered, comparison of the open- and semiclosed-cycle engines showed the open-cycle power system would require less fuel for the same total system weight, or that it would have lower total weight for the same fuel expenditure. Also, the recuperated open-cycle engine resulted in lower total weights than the unrecuperated open-cycle engine. Although the unrecuperated engine is lighter, its higher fuel consumption (particularly at partial power operation) results in significantly higher fuel and fuel system weight.

For the transportation applications considered, the semiclosed Brayton was lighter than a closed Brayton engine at the same design point efficiency and, thus, more efficient than a closed Brayton with the same engine weight. Of the variations of closed-cycle engines considered, group II (using an integrated combustor and heat-source heat exchanger and near stoichiometric air-fuel ratio) was lighter and more efficient than group I (using a conventional diluent controlled combustor). This was due to the lighter, more efficient combustion loop of group II engines.

These weight and performance comparisons are peculiar to the type of applications considered. In some applications, where the working fluid must be conserved or contained, there is no tradeoff, and the selection must be closed cycle. Examples are applications where the working fluid is other than air, exoatmospheric (space or underwater applications), or direct-cycle gas-cooled reactors where the working fluid becomes radioactively contaminated. When waste heat can be rejected to water the conclusions may be different. In this case it is the gas side that will control waste exchanger size and weight. The closed or semiclosed systems will now benefit (on a weight basis) from the higher pressure level, which will also reduce the other system component sizes and weights. In this situation the closed or semiclosed system might be smaller and lighter than the open recuperated system and other factors will affect selection more significantly (cost, reliability, and maintainability, for example).

When a substantial fraction of waste heat is otherwise utilized, the conclusions again change. Now, a waste heat exchanger is part of the system by definition, and it would be advantageous to investigate closing or semiclosing the loop to exploit the benefits of increased pressure level. When rapid response to transients is a requirement of the application, semiclosed and open-cycle engines are the most attractive. The semiclosed engine incorporates built-in inventory control by virtue of the turbocharger. But a closed-cycle engine would require an auxiliary system to provide inventory adjustment, which could be a substantial weight penalty, depending on the response requirements.

For the heavy-duty transportation applications considered, the open-cycle Brayton engine using an infinitely variable speed transmission has fuel economy comparable to that which could be obtained with closed and semiclosed engines. Since it has no waste heat exchanger, it has lower engine weight and volume. In addition, since it is the waste heat exchanger that dominates engine-vehicle integration problems, the open-cycle engine offers greater flexibility of application.

All of the Brayton cycles considered have the flexibility to use a variety of combustor types. As studied, the group II engine, which uses a surface combustor by definition, would have the lowest undesirable exhaust emission levels. However, the surface combustor could also be used with semiclosed and open cycles to reduce their emissions to near the level possible with the closed cycle. In addition, a catalytic combustor with the potential for very low emission levels could be used for all these cycles. Considering conventional diluent-controlled combustors, the closed-cycle engine would have the lowest emission levels.

Of the engines considered, the closed cycles would be the quietest with noise levels less than 75 dBA at 50 feet. Their dominant noise sources are those external to the power conversion loop, that is, coolant and combustion air fans and the transmission. In addition to these, the semiclosed cycle would have the turbocharger and exhaust gas rejection as noise sources. The dominant noise source in the open-cycle engine would be the compressor inlet. With acoustic treatment of the compressor inlet and of the engine compartment, both the full power operation of the semiclosed and open cycles could be quieted to less than 80 dBA at 50 feet.

Considering these discussions, some more general conclusions concerning selection between open, closed or semiclosed Brayton cycles are obvious. The closed cycle is appropriate where a closed loop is required, where waste heat is utilized, or where heat rejection is not to the atmosphere. The semiclosed cycle is appropriate where waste heat is utilized or rejection is not to the atmosphere and where lower partial power operation and better transient response than the closed cycle are required. The open cycle applies where low volume, weight, and specific fuel consumption are required coupled with rapid transient response and where heat rejection is to the atmosphere.

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